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EFFECTS OF THERMAL STRATIFICATION UPON OXYGEN RESOURCES, JOHN H. KERR RESERVOIR

Robert Horn, et al

Federal Water Pollution Control Administration
Charlottesville, Virginia

June 1968

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EFFECTS OF THERMAL STRATIFICATION UPON OXYGEN RESOURCES

JOHN H. KERR RESERVOIR

Interim Report

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Middle Atlantic Region
FWPCA
June 1968

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EFFECTS OF THERMAL STRATIFICATION UPON OXYGEN RESOURCES JOHN H. KERR RESERVOIR

Interim Report

BY

C. Robert Horn

and

Russel H. Wyer

I

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II. SUMMARY

During the 1967 stratification period, a study was made of the oxygen resources of the John H. Kerr Reservoir and Roanoke River. Vertical sections of dissolved oxygen and temperature were sampled at fourteen stations in the reservoir throughout the summer. These parameters were monitored continuously in the tailrace and several times at nine stations along the course of the river below the dam.

The study showed that thermal stratification takes place in the reservoir between June and September; and from temperature measurements taken in 1964, 1965, 1966, and 1967, it appeared that the behavior of the reservoir with respect to stratification was similar for all years.

The thermocline is most clearly defined in July and August. Its surface varies in depth from 20 to 40 feet depending upon seasonal temperature variations. Dissolved oxygen concentrations in the hypolimnion generally range from 0.0 mg/l to 2.5 mg/l throughout the reservoir in July, August, and the first weeks of September.

Most of the water passing through the penstocks is drawn from the oxygen deficient hypolimnion resulting in contravention of State Water Quality Standards immediately below the dam for approximately two months each summer. In the next 10 miles of river, the water quality is improved through reaeration which increases the dissolved oxygen content of the river by approximately 2.0 mg/l.

Downstream dissolved oxygen conditions cannot be significantly improved by selective operation of particular generators, and no significant relationship exists between magnitude of discharge and dissolved oxygen in the tailrace.

A direct relationship was found between dissolved oxygen in the tailrace and that at the 60-foot depth, 1,000 feet upstream from the dam, which can be used as a pilot study control. The relationship can be expressed in equation form as

$$DO_{tr} = DO_{60} + 0.3$$

in which DO_{tr} is dissolved oxygen in the tailrace and DO_{60} is dissolved oxygen at the 60-foot depth, 1,000 feet above the dam.

It is desirable to have the control point located at a station one mile upstream from the dam so that it will not be influenced by pilot study destratification operations. It was found that the dissolved oxygen at the one-mile station was essentially the same as that at the 1,000-foot station in 1967, but additional data should be collected at these stations to verify this relationship.

in which DO_{tr} is dissolved oxygen in the tailrace and DO_{60} is dissolved oxygen at the 60-foot depth, 1,000 feet above the dam. This relationship can be used as a pilot study control if the control point is located at the one-mile station in the reservoir rather than the 1,000-foot station. This is necessary to insure that the control will not be influenced by pilot study destratification operations. Additional sampling will be required in the reservoir to locate the control point at the one-mile station.

III. RECOMMENDATIONS

It is recommended that:

1. During the 1968 stratification period, temperature and dissolved oxygen sampling be resumed at the 1,000-foot station in June on approximately a bi-weekly basis.
2. Sampling be conducted concurrently at the 1,000-foot station and the one-mile station, on a weekly basis, from the middle of July until the latter part of August with samples being taken twice during the last week of July and twice during the first week of August.
3. A pilot study for destratifying Kerr Reservoir be conducted during the 1969 stratification period and that the water quality control device be installed prior to July 1, 1972, in order to be in compliance with the Virginia Water Quality Standards and Presidential Executive Order 11288.

IV. BACKGROUND

The John H. Kerr Reservoir, shown on the Basin Map, is located in Virginia on the Roanoke River, which is an interstate stream. It was built in 1952 as a multiple purpose peaking power, flood prevention, and recreation reservoir with a total normal storage capacity of 1,530,000 acre-feet. The normal depth of the lake just above the dam is 100 feet. Downstream, a distance of 42 miles, is the Roanoke Rapids Reservoir which was built in 1955 by the Virginia Electric and Power Company (VEPCO) for peaking power purposes with an 85,000 acre-foot normal pool and a depth just above the dam of 62 feet. In 1953, VEPCO applied for a license to change the design and electrical capacity of the Roanoke Rapids Project. Objection to this application by intervening parties concerned with the quality of releases from reservoirs on the river led to the construction, in 1957, of a submerged weir in the Roanoke Rapids Reservoir. The weir is constructed of crushed stone and is 800 feet long with its two ends tied to the upstream face of the dam on either side of the turbine intakes. The crest of the weir is 25 feet below the normal pool elevation.

An intensive study to determine the effectiveness of the weir was made in the summer of 1957 under the cooperative efforts of the Division of Water Pollution Control, North Carolina State Board of Health; North Carolina Wildlife Commission; Virginia Electric and Power Company; the U. S. Fish and Wildlife Service; and the U. S. Public Health Service. The studies proved the weir was effective in preventing the releases of oxygen deficient hypolimnetic water from the lower depths of the

reservoir except after large upstream releases from the John H. Kerr Reservoir. When inflow from the Kerr Reservoir was large relative to the storage capacity of Roanoke Rapids Reservoir, the oxygen deficient water from the lower depths of Roanoke Rapids Reservoir was displaced over the submerged weir into the turbine intakes resulting in low dissolved oxygen concentrations downstream.

In 1962, VEPCO expanded its peaking power facilities on the Roanoke River with the construction of the Gaston Reservoir As a result of the 1957 study, a submerged weir was constructed around the turbine intakes with its crest positioned 15 feet below the lake surface to select water of highest possible dissolved oxygen content for discharge from the reservoir. The weir was made 1,000 feet long to satisfactorily minimize reduction in power generation that would be caused by head loss across the weir.

The Gaston Dam is located on the Roanoke River between the Roanoke Rapids Reservoir and the Kerr Reservoir eight miles upstream from the Roanoke Rapids Dam. Its total storage capacity is 400,000 acre-feet, and its depth at the dam is approximately 70 feet. Since the storage capacity of the Gaston Reservoir was much larger than that of the Roanoke Rapids Reservoir, the problem created by large cool water releases from the Kerr Reservoir on the quality of releases from the Roanoke Rapids Reservoir was expected to be considerably reduced.

In addition to the problem created by large cool water releases from the Kerr Reservoir, the water released from the

reservoir is deficient in dissolved oxygen, often causing contravention of State Water Quality Standards in the first 10 miles of river below the dam. The Roanoke River is an interstate stream, and the beneficial uses of the river between the Kerr Dam and the Gaston Dam are public and municipal water supply, recreation, and propagation of fish and wildlife. The Virginia and North Carolina Water Quality Standards specify a minimum of 4.0 mg/l dissolved oxygen for these uses. The distribution of the daily average dissolved oxygen concentrations in the tailrace during a typical stratification period is shown in Figure 1. This curve shows that the dissolved oxygen concentration fell below the Water Quality Standards for 56 days during that stratification period.

Vertical sections of temperature and dissolved oxygen were sampled in the Kerr Reservoir in conjunction with the 1957 study during the stratification period. These vertical sections revealed that the thermocline was located above the centerline of the turbine intakes and that the primary source of water discharged from the dam was the oxygen deficient hypolimnion.

Sampling at one station in the reservoir and at downstream stations was continued during stratification periods, and in 1966 the Federal Water Pollution Control Administration installed an automatic water quality monitor in the tailrace of the Kerr Dam. The monitor continuously senses and records the temperature and dissolved oxygen concentrations of the water released from the reservoir. Early in 1967, the Corps of Engineers requested that the Federal Water Pollution Control Administration assist them with an expanded water quality study program for the Kerr Reservoir. Intensive sampling of dissolved oxygen concentrations and temperature within the reservoir began on June 21, 1967, and continued through the middle of November.

which by definition is a stratum of water in which the temperature decreases by 0.55°F or more in a depth of one foot. As can be seen in Figure 2, which shows the thermal stratification in the reservoir on July 31 and August 1, the temperature gradient in the thermocline was most pronounced near the dam and became progressively less pronounced in the upstream direction.

The seasonal variations of thermal stratification at a location 1,000 feet upstream from the face of the dam are shown in Figures 3A, 3B, 3C, and 3D for the years 1964, 1965, 1966, and 1967, respectively. As can be seen by comparison of these figures, thermal stratification patterns were similar for each year considered. In 1967, the thermocline developed in June; and as the season advanced, it became progressively more pronounced until the first of August, when the temperature gradient in the thermocline began decreasing. By September 6, the gradient had decreased to the extent that the stratum could no longer be termed a thermocline. The depth of the thermocline fluctuated but had an overall downward trend as the season progressed. In June it was approximately 30 feet below the surface; and by the latter part of August, it had dropped to a depth of 55 feet. The stratum of maximum temperature gradient, while no longer considered a thermocline, dropped to a depth of 80 feet by the end of September; and the fall turnover effected a uniform distribution of temperature in the reservoir by the end of October. By November 13, the temperature was 58°F throughout the reservoir except for a small amount of water at 57°F on the bottom.

Figure 4 shows the distribution of dissolved oxygen concentrations within the reservoir on July 31 and August 1, 1967. The reason for low dissolved oxygen content of releases from the reservoir is apparent when the location of the power intakes is noted in comparison with the mass of oxygen deficient water in the reservoir.

Figure 5 shows the seasonal variation of dissolved oxygen within the reservoir 1,000 feet upstream from the dam in 1967. Dissolved oxygen concentrations below the thermocline or stratum of maximum temperature gradient remained below 2.5 mg/l and on the average were less than 1.0 mg/l from July through October; while above the thermocline, dissolved oxygen concentrations ranged between 5 mg/l and 8 mg/l, and a sharp gradient of dissolved oxygen concentrations formed within the thermocline. This sharp D.O. gradient remained within the stratum of maximum temperature gradient until the end of October when both dissipated and relatively high concentrations of dissolved oxygen became widespread throughout the depth of the reservoir. By the end of the sampling period, the dissolved oxygen at the station 1,000 feet upstream from the dam was approximately 8.0 mg/l at all depths. The seasonal variations of dissolved oxygen concentrations within the reservoir were similar at the other sampling stations.

Power Discharge Relationships to Dissolved Oxygen

In order to determine what effect power discharges have upon the distribution of dissolved oxygen within the reservoir, dissolved oxygen samples were taken at 10-foot vertical intervals, 200 feet, 500 feet, and 1,000 feet ahead of the turbine intakes before, during, and after generation. These samples were taken on July 27, August 24

September 11, and September 12. The density and frequency of sampling were not adequate to support detailed conclusions regarding movement of dissolved oxygen concentrations within the reservoir in response to flow into the turbines. However, it is apparent that under conditions similar to those during which the samples were taken, it would not be possible to significantly improve tailrace dissolved oxygen by selective operation of particular generators, since the strata from which all of the generators draw water are deficient in dissolved oxygen during the stratification period.

The relationship between dissolved oxygen and magnitude of discharge in the tailrace was also investigated. The records from the dissolved oxygen and temperature monitor in the tailrace were analyzed, along with the discharge records for the reservoir, to determine if a relationship between dissolved oxygen, temperature, and discharge exists. No relationship of any significance was found; however, a very slight amount of reaeration was evident when a comparison was made between the dissolved oxygen in the tailrace and the average dissolved oxygen passing through the cross-section of the turbine intakes. It is possible that this slight reaeration is a function of the magnitude of discharge, but it is not considered feasible to improve dissolved oxygen conditions downstream by increasing discharge from one or more of the turbines.

Dissolved oxygen and temperature measurements were made at several stations in the first 14 miles of river below the dam before, during, and

after generation. These measurements were made in 1967 on July 25 and 26, August 22 and 23, and September 13 and 14, and showed that stream reaeration increases dissolved oxygen content of the river by approximately 2.0 mg/l in the first 10 miles below the dam. An accurate assessment of the response of the river to power releases from the reservoir could not be made from the limited amount of data obtained from this phase of the sampling activity.

Pilot Study Control

An effort was made to find a relationship between dissolved oxygen in the tailrace and temperature or dissolved oxygen at some point within the reservoir for use as a control in conducting a pilot study to evaluate the effectiveness of various methods of improving the quality of water released from the reservoir. It was found that there is a good relationship between dissolved oxygen at the 60-foot depth in the reservoir, 1,000 feet above the dam, and dissolved oxygen in the tailrace. This relationship was found from an evaluation of data collected in 1964, 1965, 1966, and 1967 and is shown graphically in Figure 6. The line shown is an approximate fit through the data points and can be expressed in equation form as

$$DO_{tr} = DO_{60} + 0.3$$

in which DO_{tr} is dissolved oxygen in the tailrace and DO_{60} is the dissolved oxygen measured at the 60-foot depth, 1,000 feet upstream from the dam. The linear relationship expressed by this equation does not hold for values of DO_{60} below 1.0 mg/l. Frequent samples of

dissolved oxygen and temperature should be taken at the 1,000-foot station during the 1968 stratification period to define the relationship in this range. Envelope curves were fitted through the data points of extreme values as shown on Figure 6 to show graphically the range of values in the data set.

The relationship expressed by the above equation can be used as a control for a pilot study. By monitoring the dissolved oxygen at the 60-foot depth, the dissolved oxygen in the tailrace can be determined as though in the absence of pilot study destratification. This can then be compared with actual tailrace dissolved oxygen for evaluating the effectiveness of the destratification systems under investigation.

It is desirable to have the control point located one mile above the dam instead of 1,000 feet to remove it from disturbances that will be caused by destratification operations conducted near the dam. Table 1 shows the relationship between dissolved oxygen at the 60-foot depth, 1,000 feet above the dam, and that at the one-mile station as determined from the data collected during 1967.

Table 1

Date	Dissolved Oxygen 1,000' Above Dam at 60' Depth	Dissolved Oxygen 1 Mile Above Dam at 60' Depth
June 21	4.6 mg/l	4.5 mg/l
July 5	2.9 mg/l	2.8 mg/l
July 20	1.1 mg/l	1.1 mg/l
July 31	0.8 mg/l	0.8 mg/l
August 16	0.2 mg/l	0.2 mg/l
August 28	0.0 mg/l	0.0 mg/l
September 6	0.0 mg/l	0.1 mg/l
September 21	5.5 mg/l	5.4 mg/l
October 4	5.9 mg/l	5.9 mg/l
October 17	5.3 mg/l	5.5 mg/l
October 30	7.2 mg/l	7.8 mg/l
November 13	8.3 mg/l	8.3 mg/l

While there is good indication that the one-mile point might be used satisfactorily to predict tailrace dissolved oxygen, additional data should be collected at the 1,000-foot point and at the one-mile point to verify the correlation between these stations during the 1968 stratification period.

VI. CONCLUSIONS

The study results indicated that dissolved oxygen levels downstream from the reservoir cannot be significantly improved by modifying present operating procedures. Power releases from the John H. Kerr Reservoir cause contravention of State Water Quality Standards for dissolved oxygen in the Roanoke River for approximately two months during each summer.

Executive Order 11288 requires Federal agencies and establishments to provide the leadership example in the national effort to improve water quality through prevention, control, and abatement of water pollution from Federal Government activities in the United States. The State of Virginia requires that such operating results as are necessary to implement the State Water Quality Standards be secured no later than July 1, 1972.

Within the Roanoke River Basin, the State requires the City of Danville to comply with the standards on or before October 1, 1969. In order for the the Federal Government to provide leadership in this basin, pilot study investigations of devices for minimizing the downstream effects of thermal stratification should be made during the 1969 stratification period. The device selected during the pilot study for correcting the problem should be installed and operational by July 1, 1972.

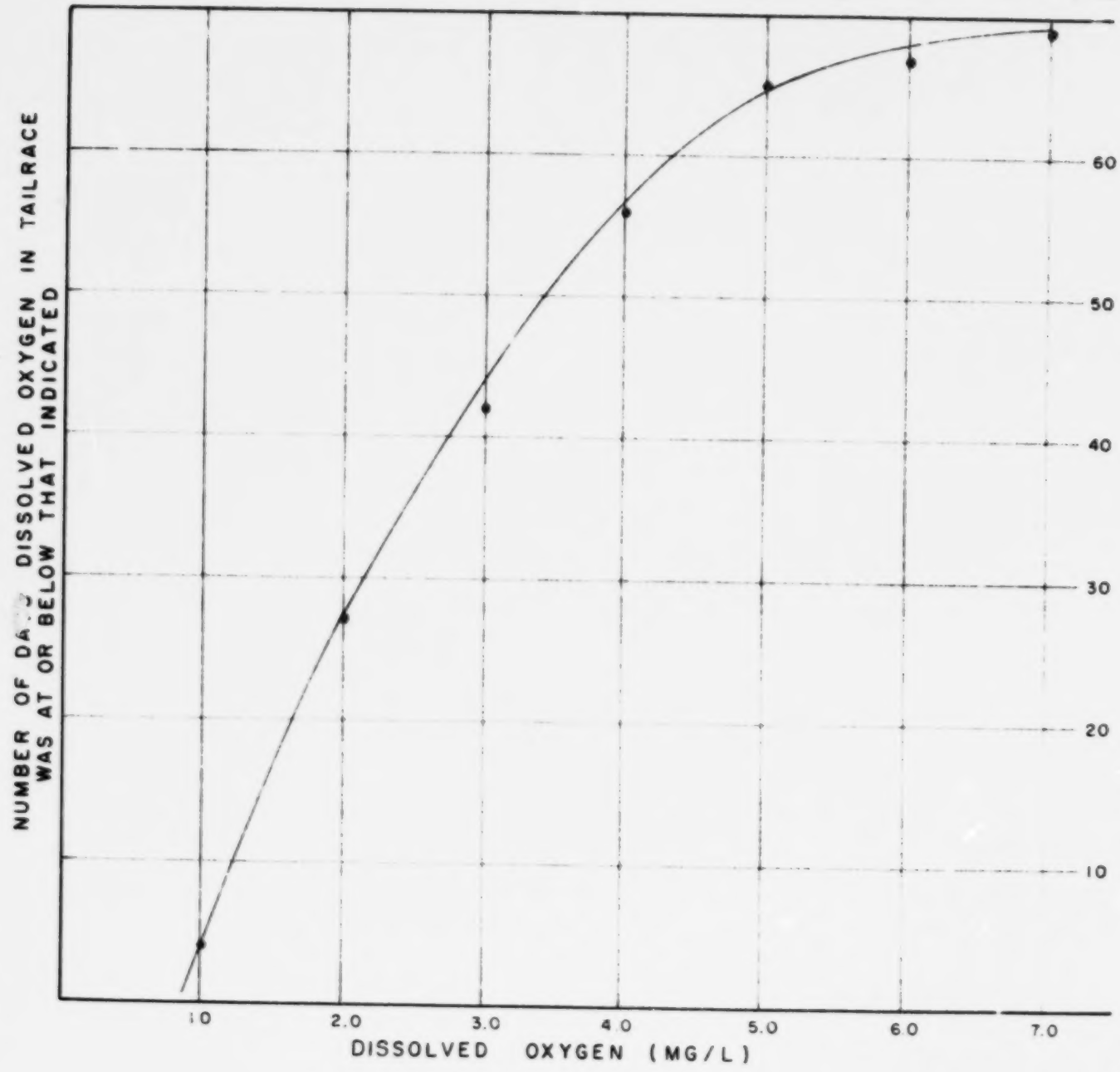

NUMBER OF DAYS DISSOLVED OXYGEN IN TAILRACE WAS AT OR BELOW THAT INDICATED
60
50
40
30
20
10
1.0
2.0
3.0
4.0
5.0
6.0
7.0
DISSOLVED OXYGEN (MG/L)

FIGURE 1

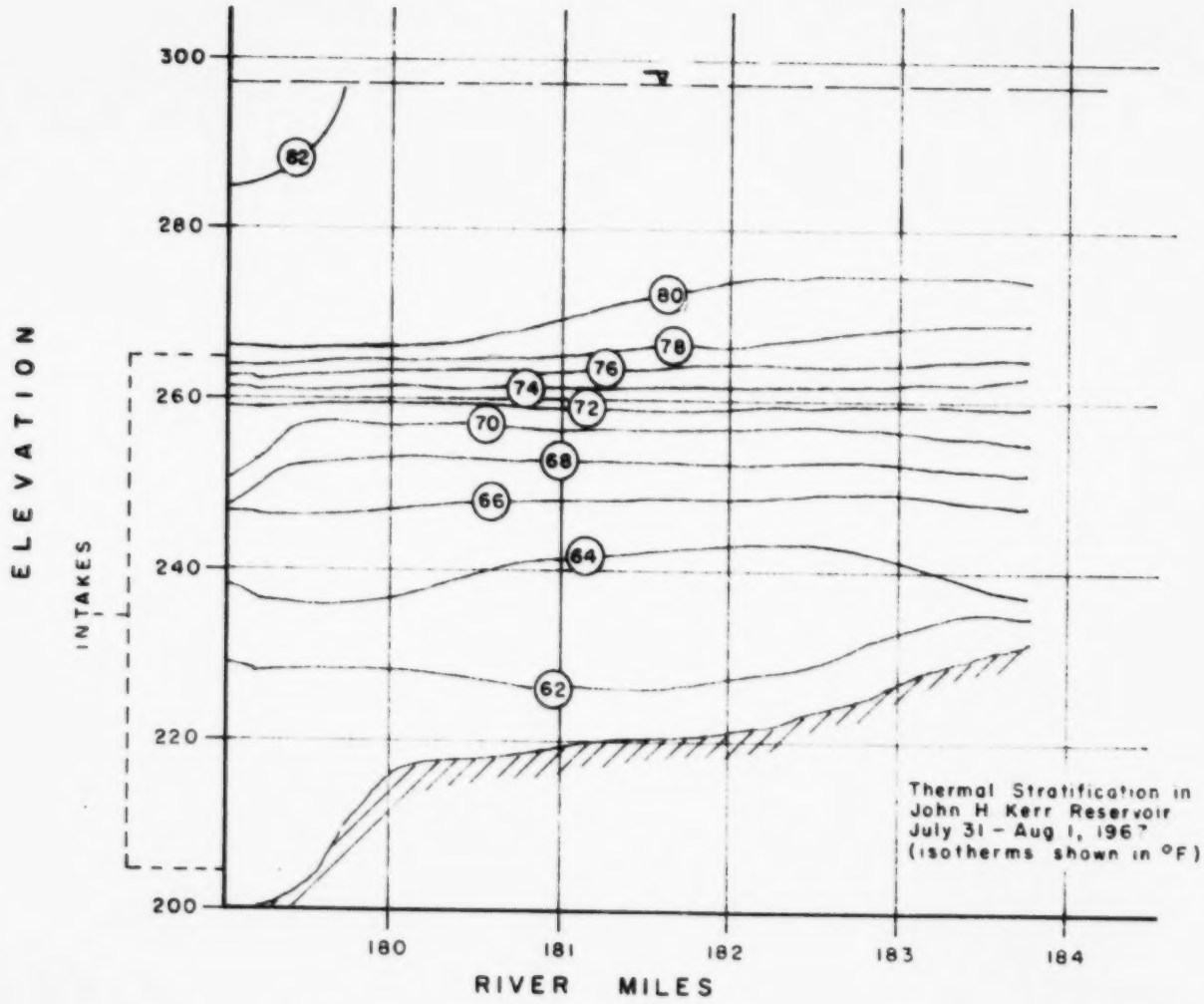
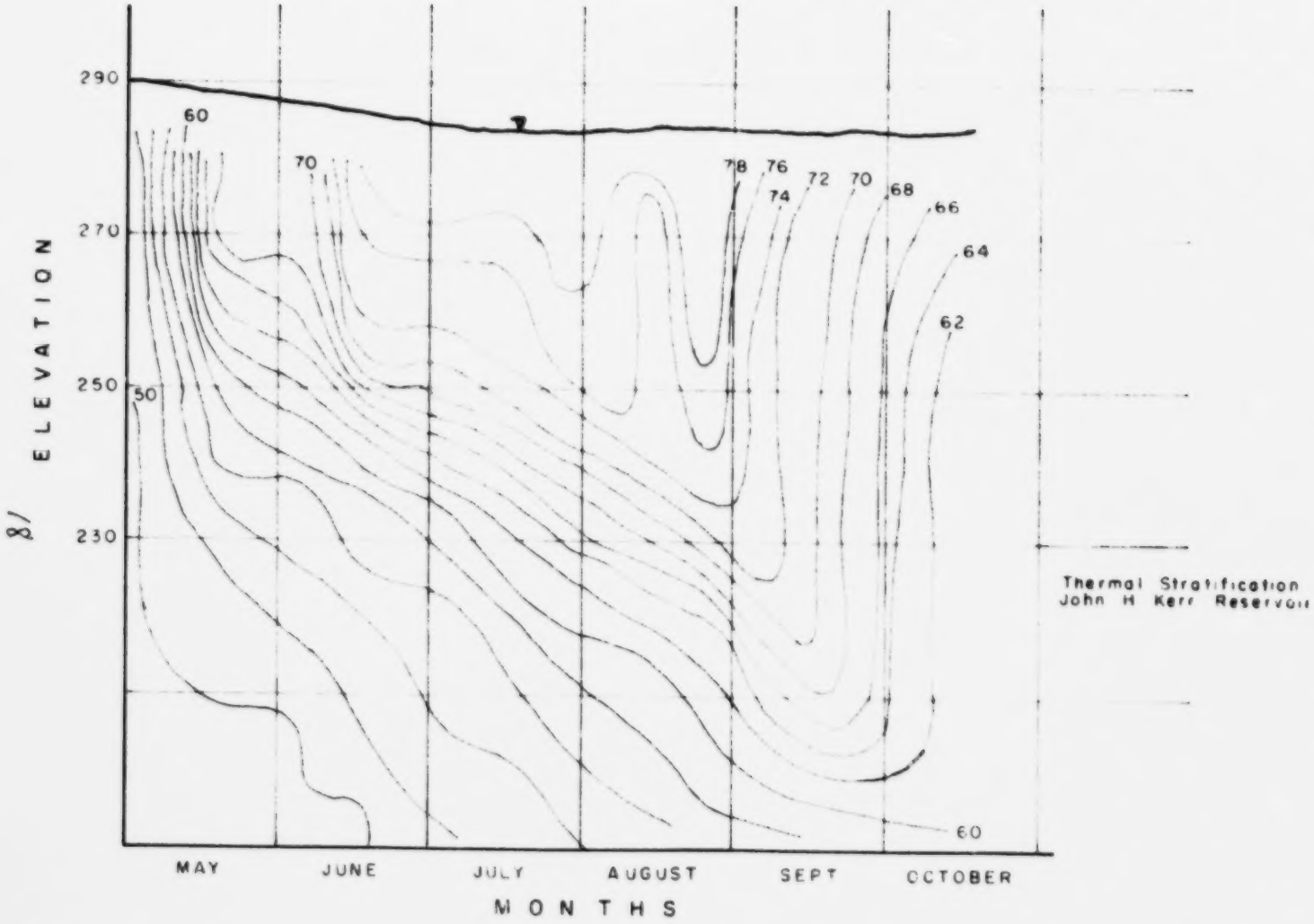
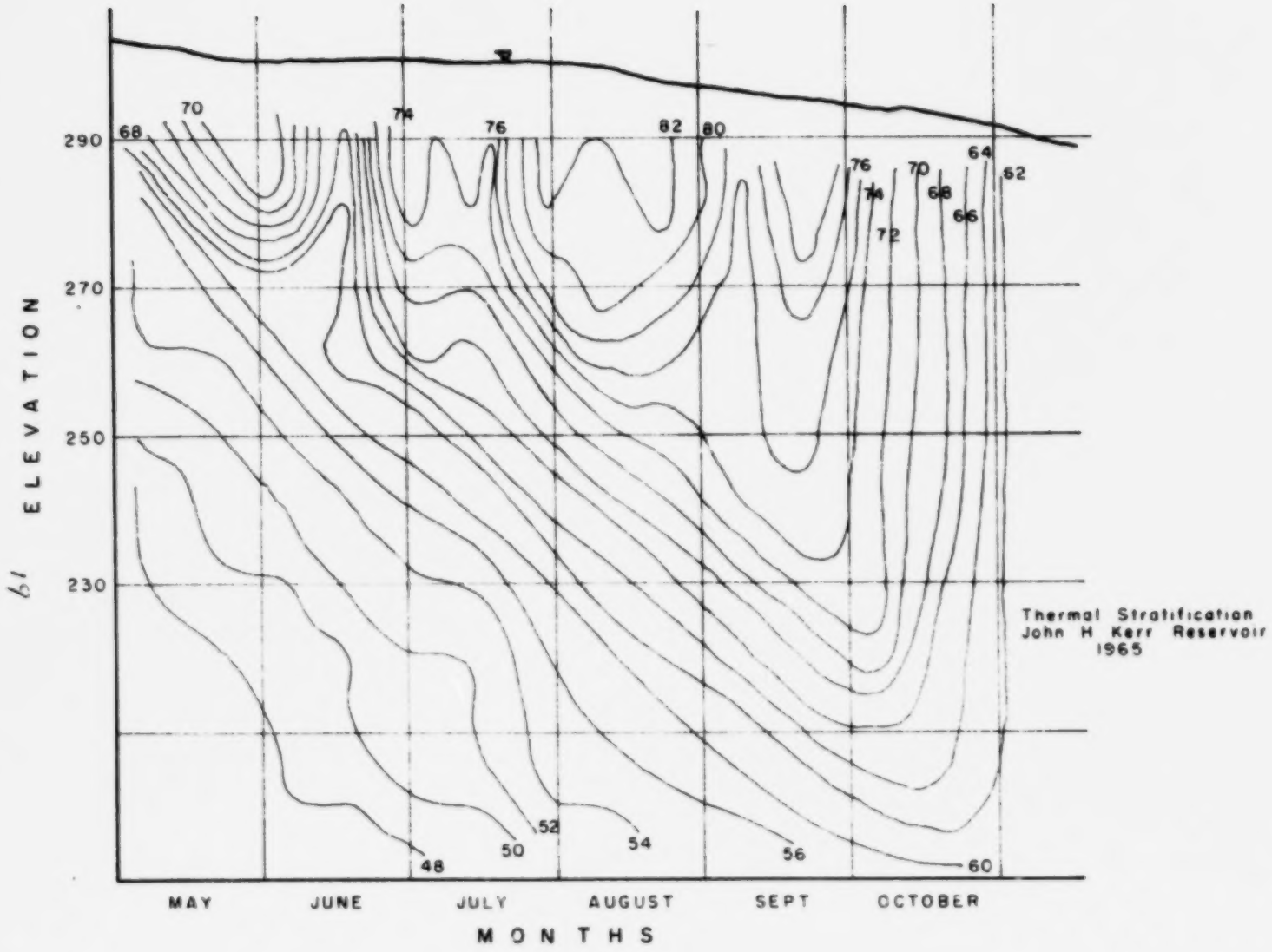

300
280
260
240
220
200
ELEVATION
INTAKES
82
80
78
76
74
72
70
68
66
64
62
180
181
182
183
184
RIVER MILES
Thermal Stratification in
John H Kerr Reservoir
July 31 - Aug 1, 1967
(isotherms shown in °F)

FIGURE 2



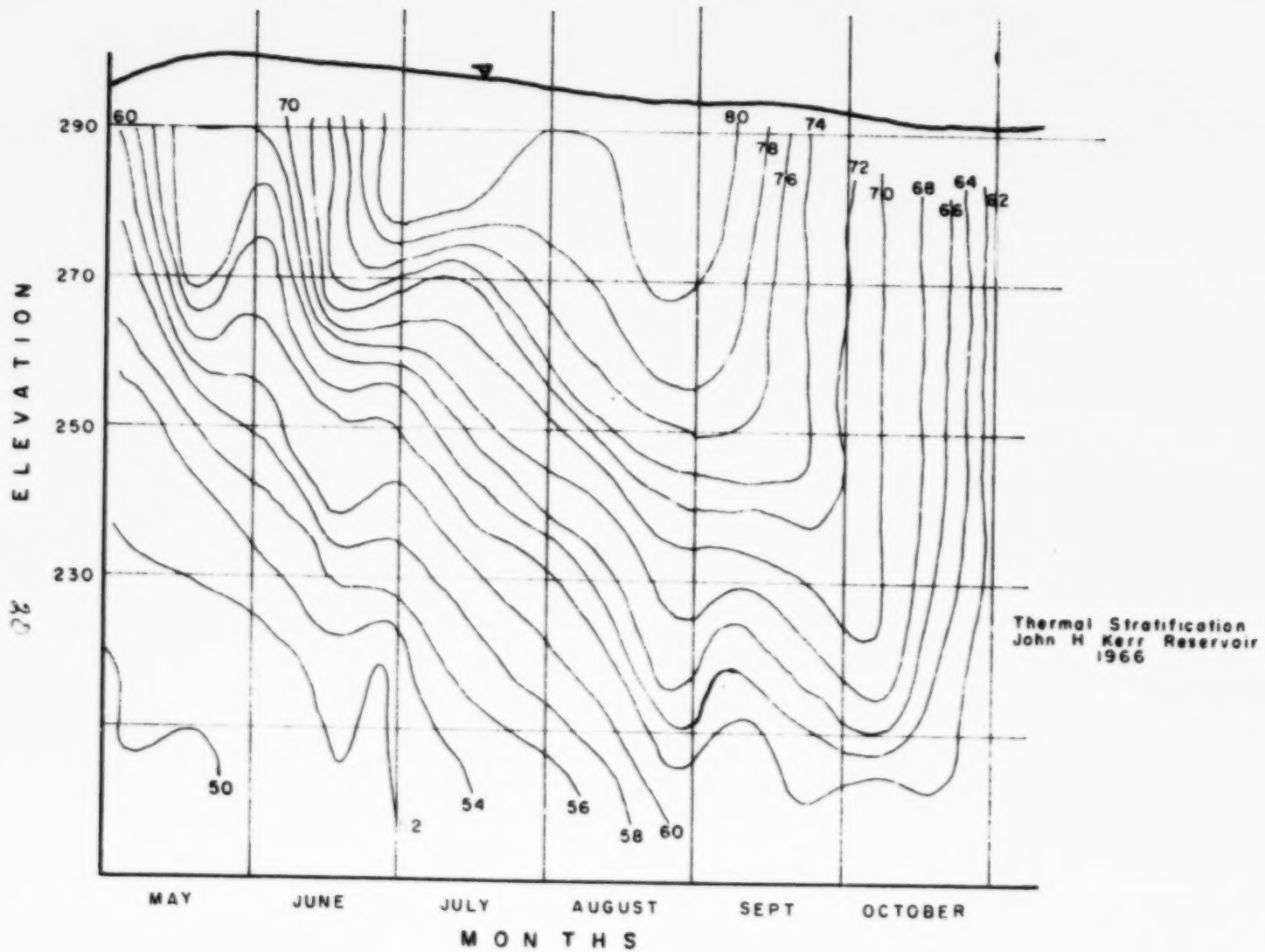
Thermal Stratification
John H Kerr Reservoir

FIGURE 3A



Thermal Stratification
John H Kerr Reservoir
1965

FIGURE 3B



Thermal Stratification
John H Kerr Reservoir
1966

FIGURE 3C

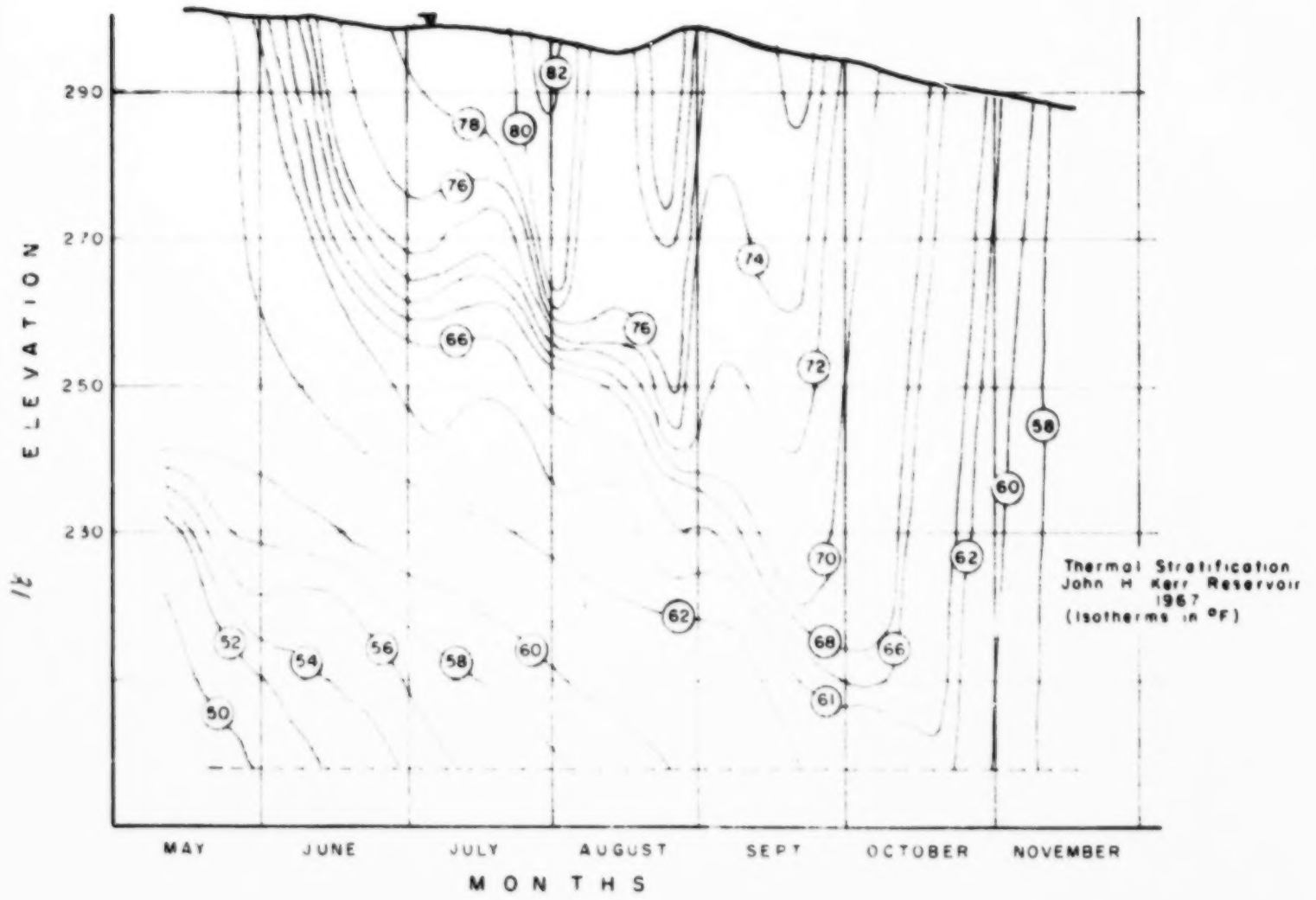

ELEVATION
290
270
250
230
MAY
JUNE
JULY
AUGUST
SEPT
OCTOBER
NOVEMBER
MONTHS
82
78
80
76
66
74
76
72
58
60
70
62
62
68
66
61
52
54
56
58
60
50
Thermal Stratification
John H Kerr Reservoir
1967
(Isotherms in °F)

FIGURE 3D

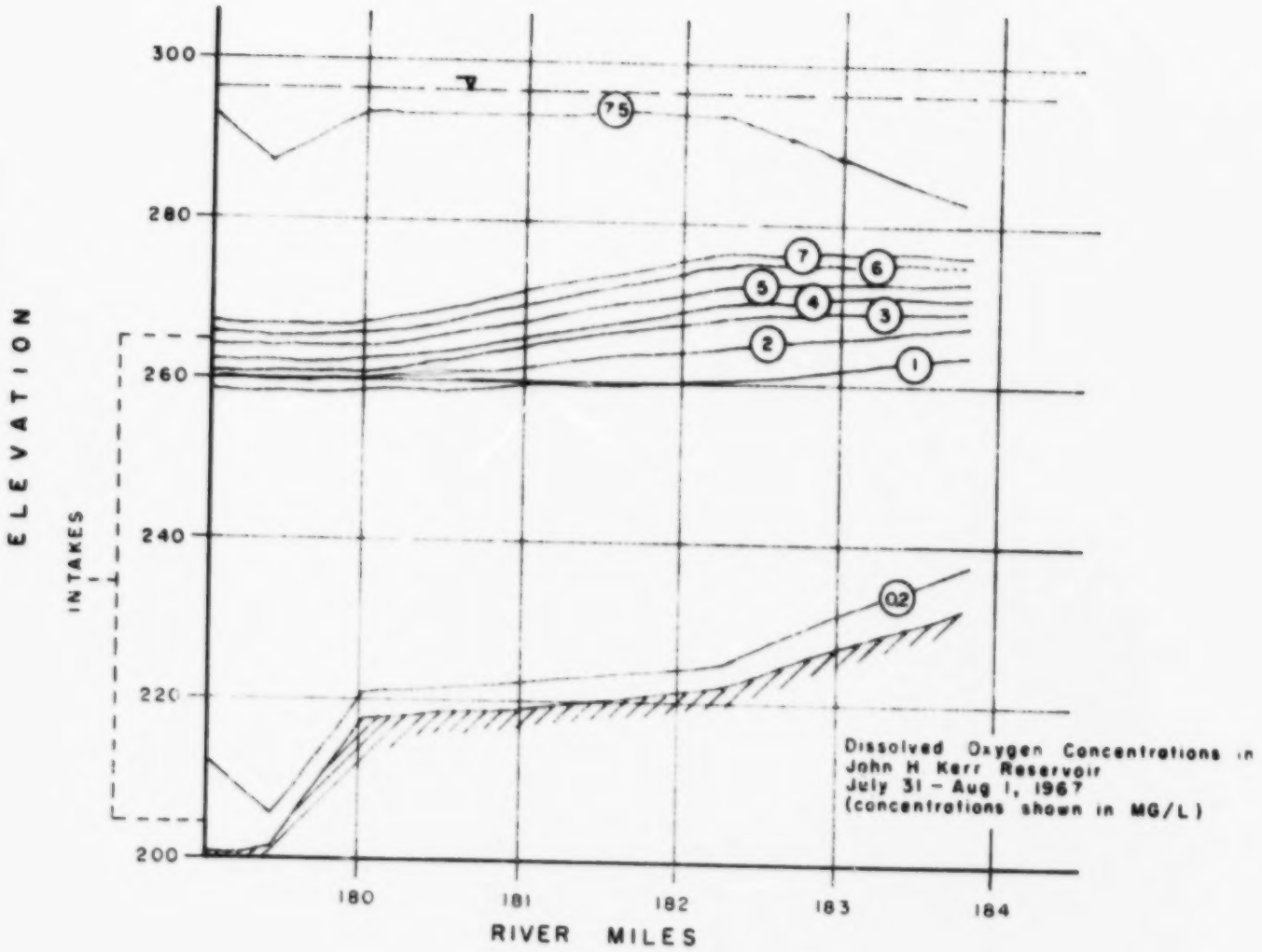
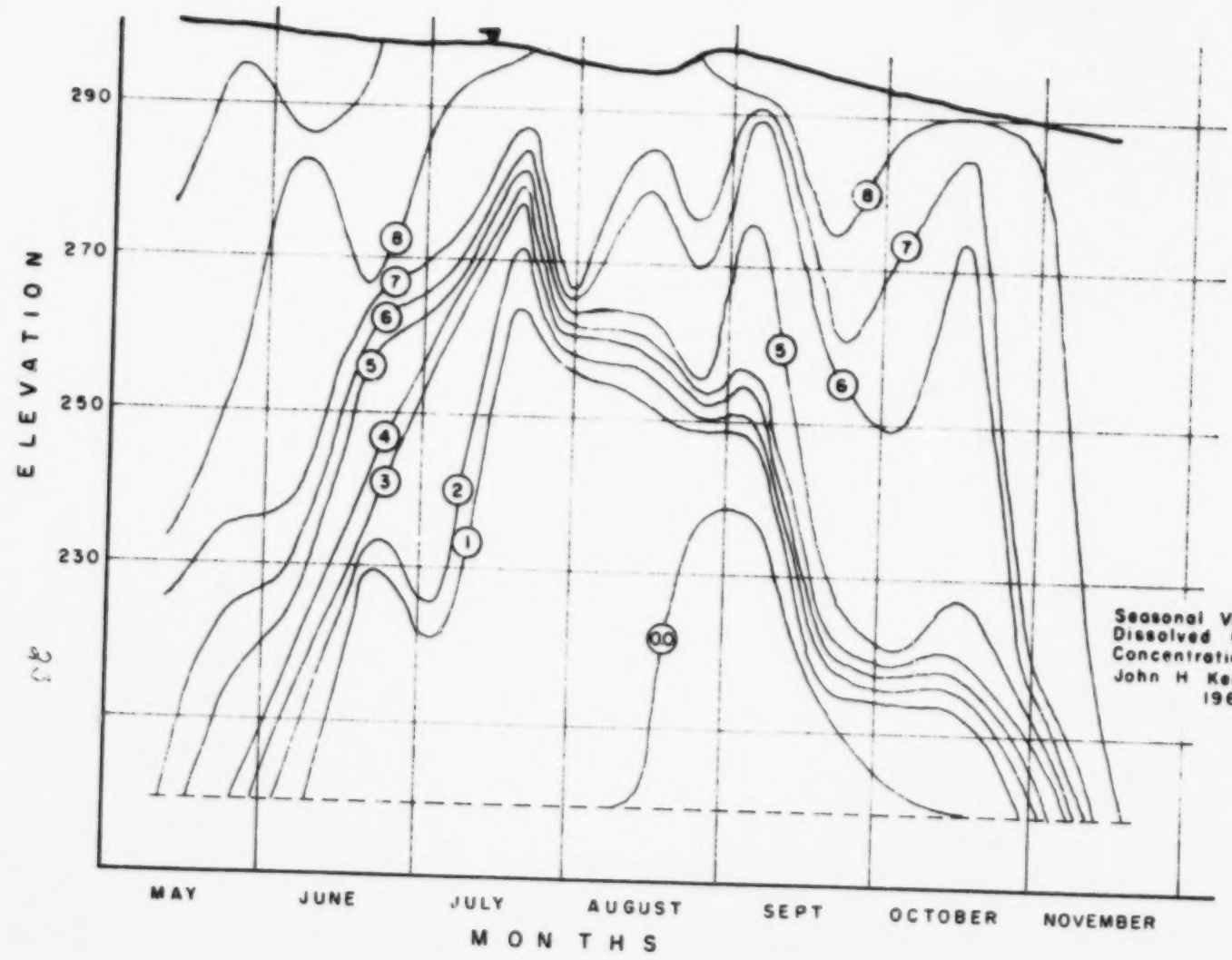

ELEVATION
INTAKES
300
280
260
240
220
200
180
181
182
183
184
RIVER MILES
7.5
7
6
5
4
3
2
1
0.2
Dissolved Oxygen Concentrations in
John H Kerr Reservoir
July 31 – Aug 1, 1967
(concentrations shown in MG/L)

FIGURE 4



Seasonal Variation of Dissolved Oxygen Concentrations (mg/l) John H Kerr Reservoir 1967

FIGURE 5

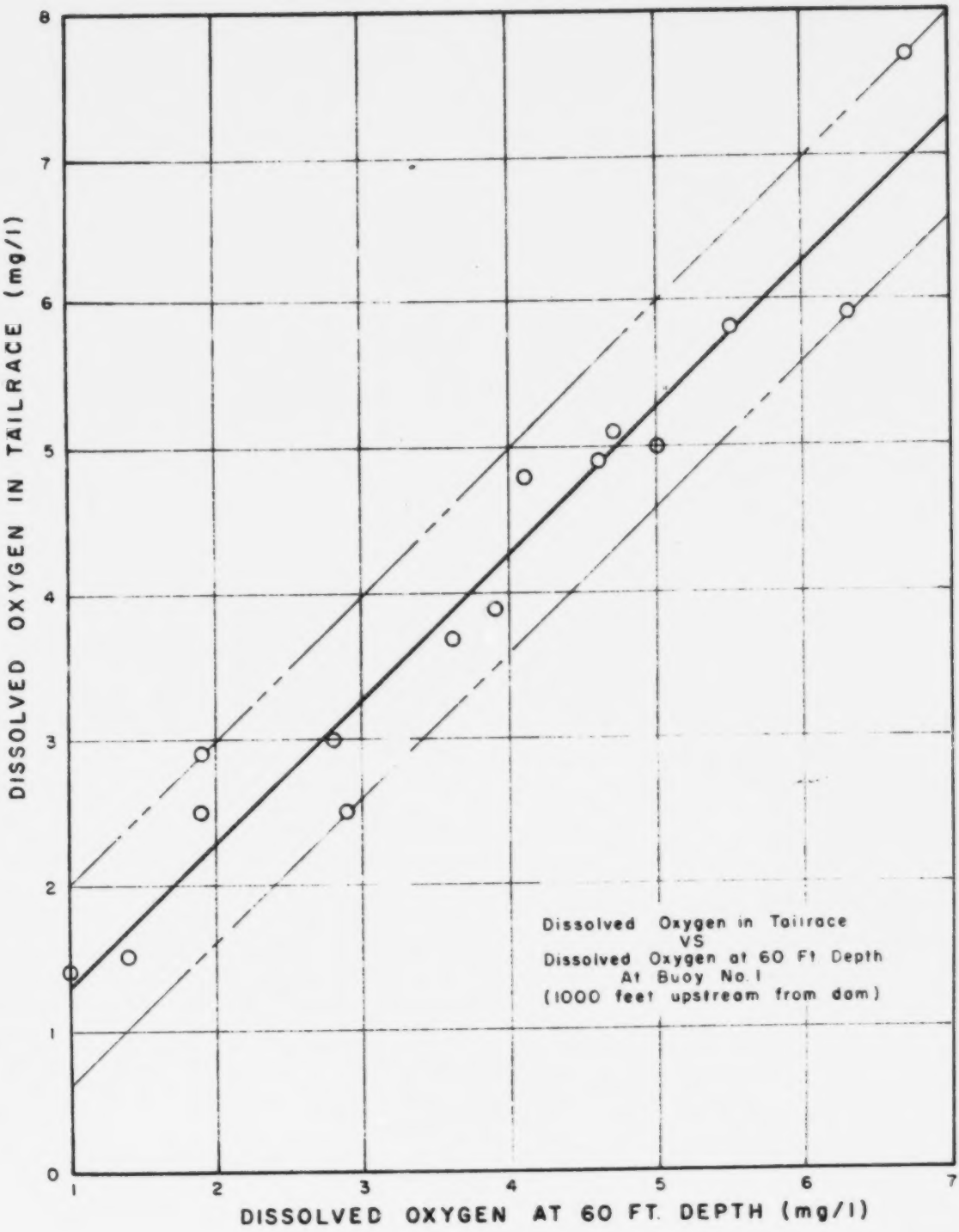

DISSOLVED OXYGEN IN TAILRACE (mg/l)
DISSOLVED OXYGEN AT 60 FT. DEPTH (mg/l)
0
1
2
3
4
5
6
7
8
Dissolved Oxygen in Tailrace
VS
Dissolved Oxygen at 60 Ft Depth
At Buoy No. 1
(1000 feet upstream from dam)

FIGURE 6

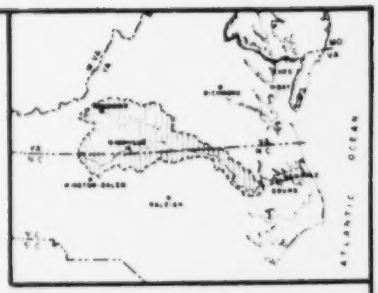
XXXXXXXXXXXXXXXXXXXXXXXX
See the following pages
for greater detail.
XXXXXXXXXXXXXXXXXXXXXXXX

ROANOKE RIVER BASIN
MIDDLE ATLANTIC DRAINAGE AREA

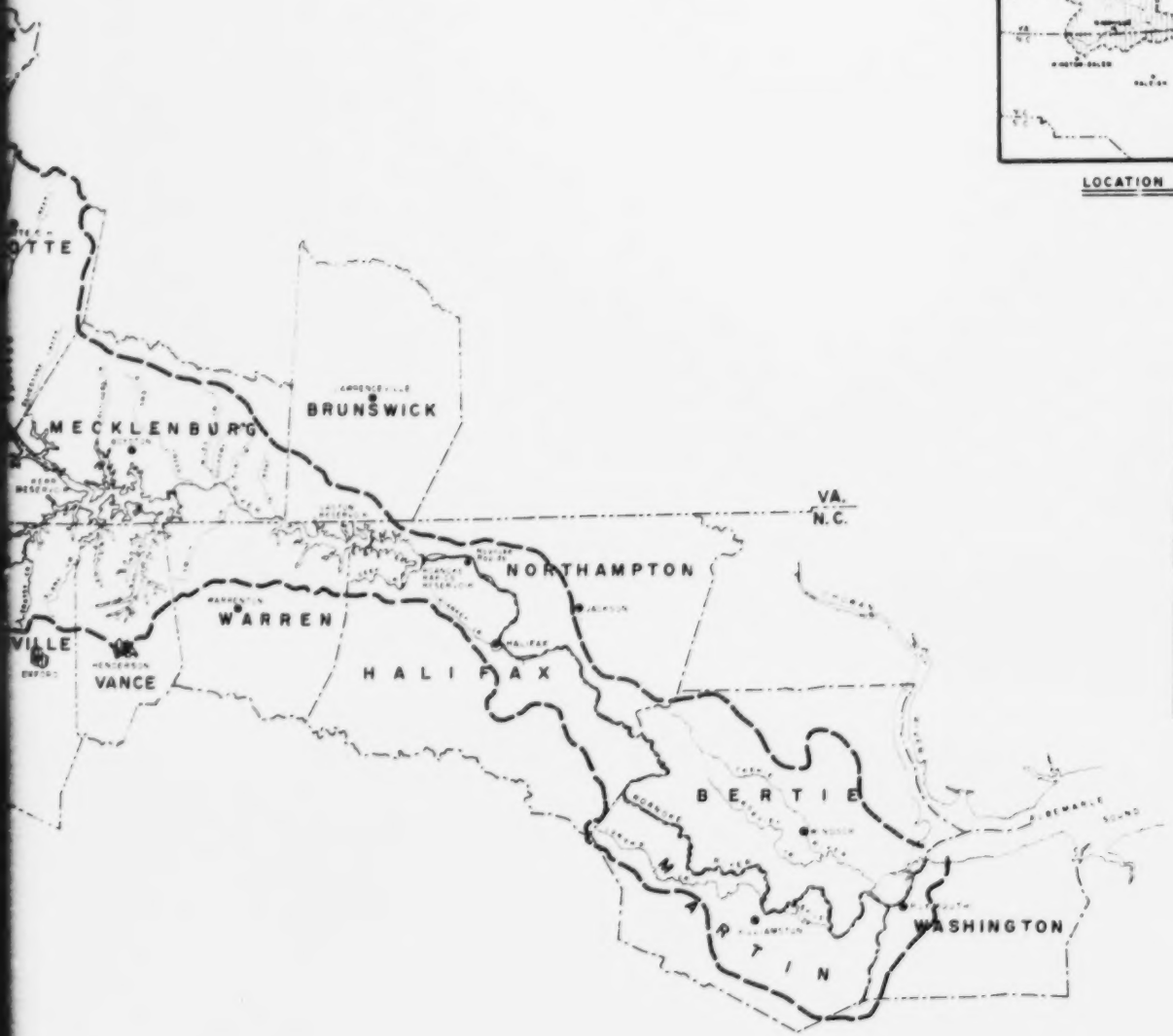
THERMAL STRATIFICATION STUDY
JOHN H. KERR RESERVOIR

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
MIDDLE ATLANTIC REGION CHARLOTTESVILLE, VA.

APPOMATTOX
BEDFORD
ROANOKE
MONTGOMERY
CAMPBELL
FRANKLIN
CHARLOTTE
FLOYD
PITTSYLVANIA
HALIFAX
PATRICK
HENRY
MECKLENBURG
VA
N.C.
VA
N.C.
STOKES
ROCKINGHAM
CASWELL
PERSON
GRANVILLE
VANCE
WARREN
FORSYTH



LOCATION MAP



ROANOKE RIVER BASIN
MIDDLE ATLANTIC DRAINAGE AREA

THERMAL STRATIFICATION STUDY
JOHN H. KERR RESERVOIR

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
MIDDLE ATLANTIC REGION CHARLOTTESVILLE, VA.

25.2